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Procedia CIRP 14 (2014) 564 – 569

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6th CIRP International Conference on High Performance Cutting, HPC2014

Sustainability Indicators for Finishing Operations based on Process Performance and Part Quality

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Abstract

Production engineers need to focus increasingly on the sustainability of manufacturing processes. Unfortunately, there are a confusingly high number of sustainability indicators available and they mostly focus on energy and material efficiency. These indicators are, however, not all appropriate for finishing operations. For example, many efficiency indicators relate to the material volume processed, but since the volume is very small in finishing operations, the material removal rarely is the best indicator. This paper discusses more appropriate efficiency indicators for finishing operations which are calculated as ratio of change in process performance or part quality divided by the needed resources. Three efficiency indicators based on average roughness, average peak-to-valley height and subjective part quality are then used in a case study on vibratory grinding. This study provides a starting point to apply more diverse performance and quality-oriented indicators for finishing processes.

Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: sustainable manufacturing processes; vibratory grinding; sustainability indicators; perceived quality

1. Motivation

Sustainability of manufacturing processes and abrasive machining is of high importance to production engineers [1]. More and more law enforcements to protect the environment and workers get in place and more and more consumers ask for products that are more sustainable in their production and use phase. Companies that incorporate sustainability into their operations can gain a competitive advantage. However, choosing and standardizing the best indicators to evaluate the sustainability of manufacturing processes is challenging. There are many sustainability indicators available, but these indicators mostly focus on energy and material efficiency [2]. For finishing operations these indicators are not good enough as they often relate to the processed material removal volume, which is very small in finishing operations [3]. In addition, the goal of most finishing operations is to produce high quality surface finish and accurate part dimensions. Due to the lack of proper sustainability indicators, we propose distinct efficiency indicators for finishing operations in section 2 and perform a case study using some of the proposed indicators on vibratory grinding.

Vibratory grinding is used for finishing operations such as deburring, edge preparation or improving part aesthetics. In section 3, the relevant process components are discussed shortly in an input-output diagram. In this study, we used a vibratory grinding machine in order to improve the machined surface roughness. The roughness, which changes over the consumed energy and time, has been considered as a sustainability indicator as well as the perceived quality over energy and time. A series of experiments exemplify how these indicators allow decisions on a sustainable finishing operation.

2. Sustainability indicators

2.1. Common approaches to evaluate sustainability

Life cycle assessment (LCA) is an established method to measure environmental impacts of products or processes. This method, however, needs detailed data collection and a thorough process understanding. Sustainability indicators are simpler to use. They are single values based on measured

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Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting
doi:10.1016/j.procir.2014.03.017

and/or estimated data that have to be normalized, scaled and aggregated consistently [2]. Sustainability indicators have the advantages of quicker data collection, easier visualization, use of qualitative data, and the opportunity to cover economic, social and environmental dimensions of sustainability [4]. Several indicators can be displayed in a target plot [5], grouped in different indexes [6], or combined and weighted through utility analysis [4] or multi-criteria decision making methods [7].

As indicated, sustainability indicators need to be normalized in order to be compared (equation 1). Normalization factors can be the number of products produced, value added, person-hours, product lifetime, etc. [2, 8]. The choice of the normalization factor, however, changes the outcome and needs thorough consideration [4].

$$\text{Sustainability Indicator} = \frac{\text{resource}}{\text{normalization Factor}} \tag{1}$$

Another common indicator is eco-efficiency, which can be defined as product or service value divided by the environmental impact (equation 2) [9, 10, 11]. In most cases, eco-efficiency is used for ecological optimization of an overall system while including economic factors [12]. Environmental impacts can be based on the consumption of raw materials, the consumption of energy, the resulting emissions, the toxicity potential, and the abuse and risk potential [12].

$$\text{Eco-efficiency} = \frac{\text{product or service value}}{\text{environmental impact}} \tag{2}$$

Some studies on manufacturing processes analyze the environmental impact through the specific energy, defined as energy divided by the material volume removed (equation 3). Gutowski et al. show that grinding uses more electricity per unit volume than processes with a higher material removal rate such as machining [3]. The trend that higher material removal rates decrease the specific energy for the same volume of material removed is well known [9, 13, 14].

$$\text{Specific energy} = \frac{\text{energy}}{\text{material removed}} \tag{3}$$

However, energy per material removed works well for a small scope just regarding the manufacturing process or processes where material removal is the main goal, but it is misleading if the process results vary a lot. For example, when a grinding wheel wears the specific energy changes a lot [9, 15]. In this case, taking an average value is misleading because the product quality differs.

Even though the specific energies per material volume removed by finishing operations are comparatively high [3], the absolute energies are still low due the fact that very little material is removed during finishing operations [1]. Moreover, research papers are often unclear about which energy they use (processing or theoretical energy, or total energy including machine energy as defined in [14]).

It is therefore obvious that indicators based on material removal are not ideal for sustainability assessment, but the focus should be on surface quality or material efficiency [1]. Suggestions are given in the following section.

2.2. Performance or quality based efficiency indicators

To overcome the described challenges in discussing sustainability of finishing processes, we propose an efficiency sustainability indicator. Efficiency is a fundamental metric to evaluate the ratio of output to input.

In a generic process, resources (energy, raw material, auxiliary materials, etc.) are added as input into a process performed with enablers (the worker, the machine, etc.) (Fig.1). The process can be defined by performance indicators (material removal rate, forces, etc.). The final part is characterized by quality parameters (surface roughness, value, friction coefficient, etc.).

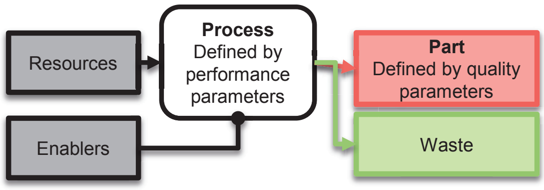

Fig. 1. Generic process flow diagram.

Table 1 lists example input and output metrics of finishing processes. Still, the process performance itself might be a necessary focus of sustainability analysis, so performance parameters for the process are also given. The efficiency indicator, η_{sust}, can be then defined by equation 4. For example, the higher the sales price of the final product with a limited amount of resources, such as time or energy, the greater the efficiency becomes. However, the target parameter needs to be kept in mind and decides on the sign. Roughness or friction coefficient, for example, should be minimal after the process, whereas other parameters should be maximized (e.g. quality, worker comfort, material removal rate).

$$\text{Efficiency Indicator, } \eta_{sust} = \pm \frac{\Delta\,\text{performance}/\Delta\,\text{quality parameter}}{\Delta\,\text{resource}} \tag{4}$$

+ when the process is meant to increase the performance or quality parameter
- when the process is meant to decrease the performance or quality parameter

Table 1: List of example resources, performance and quality parameters to determine efficiency sustainability indicators.

Input: **Resources**	**Process:** **Performance parameters**	**Output:** **Quality parameters**
• Time • Energy • Water consumed • Material used • Labor cost • Waste disposal • etc.	• Material removal rate (MRR) • Worker comfort • etc.	• Friction coefficient • Aesthetic value of product • Sales price • Part life/ part performance • Surface integrity, e.g. roughness values • etc.

This simple definition of the efficiency indicator allows addressing the areas of highest concern. For example, economic concerns are focused on when taking time or labor costs as the resource in the denominator. A social scope is addressed when, for example, the worker comfort is a performance indicator. The explicit exposure of part quality parameters distinguishes this approach from other sustainability indicators.

Though the quality parameters related to the part function or product life are much harder to quantify than other measurable parameters, efficiency indicators based on part performance and life give a true perspective of the product life cycle. Because finishing operations often dictate product performance, a leveraging effect can take place, where the efforts applied in the manufacturing phase lever the efforts in the product use phase [16]. The following section shows a practical application of three efficiency indicators and how they can be normalized to be compared.

3. Case study on vibratory grinding

3.1. Overview of Vibratory Grinding

Vibratory grinding is a mass finishing method where parts are mixed in a bulk with abrasive media causing rubbing actions [17]. It is used for deburring, polishing, and cleaning. In vibratory grinding, the container is oscillated which causes relative movements between the parts and abrasive particles as well as a slow spiral motion of the entire mass within the container [18]. The abrasive media and the parts interact in different contact modes: free impact, rolling of media on part, and part-media contact with adjacent media rolling over it [19]. Despite its broad application in die and mold manufacturing, medical and aerospace engineering, vibratory grinding is not completely modeled or understood [20]. It offers great potential for fundamental research and process improvements.

The abrasive media used are either natural materials such as walnut shells, limestone, or granite or synthetic media. The synthetic media includes alumina or silicon carbide in resin or ceramic bonding materials and are pressed into certain shapes, e.g. spheres, stars, cones, etc. Additional fluid, called compound, is used to add chemical effects, such as cleaning, cooling, or inhibiting rust. [17]

In order to make the vibratory grinding process as resource efficient as possible, the interactions between all process components need to be considered and optimized [1]. A comprehensive input-output diagram, as shown in Fig. 2, helps in understanding the resource streams. The color code is similar to the diagram on general grinding in [1]. The worker, the machine and the environment affect and enable the process in addition to the resource streams. As depicted in Fig 2, processing energy, surface texture, abrasive materials composition and social aspects of workers (i.e. health, education) have a direct or indirect impact on machined or finished product and determine the nature of waste. Process flow diagrams often help in choosing appropriate sustainability indicators [21].

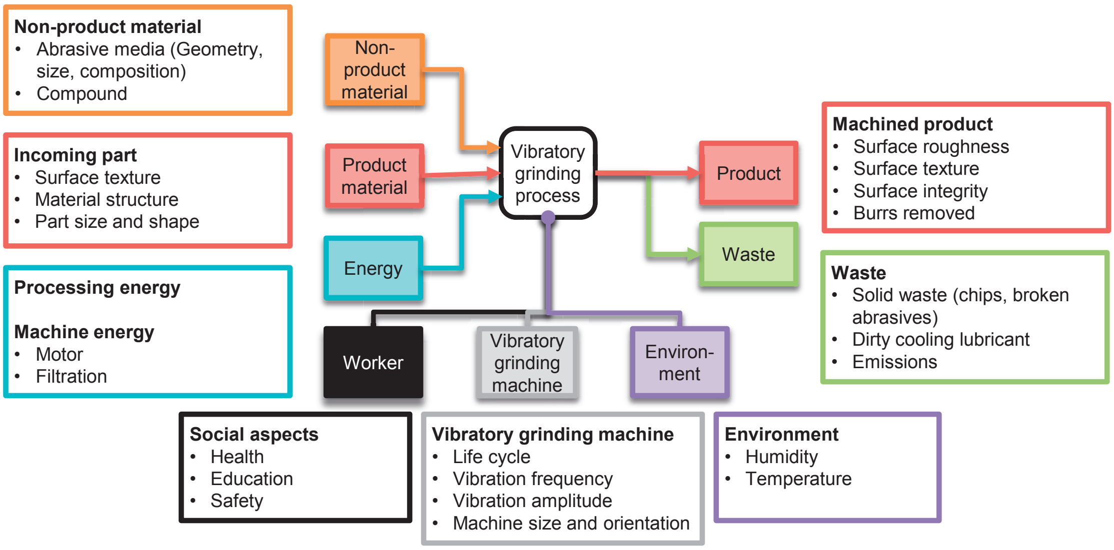

Fig. 2. Input-output diagram for vibratory grinding.

3.2. Experimental setup

The cylindrical samples for this study were made of 1018 cold roll steel (CRS) (Table 2). The samples were prepared on a manual Harrison lathe with a facing cut (depth of cut = 0.127 mm = 0.005 inch) using the slowest automatic feed rate ATX1 (25.4 mm/rev = 1 inch/rev) in order to make a common base plane for every workpiece sample. The spindle speed was 540 rpm and the material removal rate was 112.02 mm^3/min = 0.06786 $inch^3$/min.

The parts were inserted into the vibratory grinding machine, taken out after certain time periods, analyzed and put back into the container again. Wet ceramic media with a water-soap based lubricant was used as specified in Table 2.

Other process parameters, i.e. frequency and amplitude of vibration, size, shape and properties of abrasive media, were kept constant throughout the experiment.

A power meter was used to measure the energy consumption during vibratory finishing (Table 2). The low measurement frequency is justified by the long processing time of 15 min and longer. The machine drew an almost constant power of 243 W.

Table 2. Process parameters for the vibratory grinding experiments

Workpiece	
Material	1018 Cold Roll Steel
Dimensions	18.567 mm length, 25.4 mm diameter
Vibratory grinding machine	
Model	Burr King Vibra King 15
Frequency	60 Hz
Abrasive material	Medium Ceramic Abrasive : 49.6% silicon dioxide (SiO_2); 40% aluminum oxide (Al_2O_3); 5.5% potassium oxide (K_2O); 2% sodium oxide (Na_2O); 0.4% iron oxide (Fe_2O_3); 2.5% calcium oxide (CaO)
Shape, dimensions	1" angle-cut tri star
Compound	40 :1 water : soap
Power meter	
Model	Watts up Pro meter, power recordings at a frequency of one data point per 4 min 16 s

3.3. Measurement of surface quality

The surface characterization was done with a confocal laser scanning microscope (LSM700 from Zeiss). The confocal microscope can obtain 2D and 3D parameters. From a series of z level optical sections, a confocal microscope has the ability to construct and create topographic images of rough surface.

The surface quality was measured at the workpiece face with a minimum of three measurements and averaged. All the topographic data of the samples were obtained via the 20x objective under the same gain and pixel resolution condition. A typical image of the sample face observed under the confocal microscope is shown in Figure 3. This grey image shows a round shaped groove structure. We used two roughness values, the average roughness, Ra, and the average peak-to-valley height of the profile, Rz. All roughness values were measured with line profile across the grooves in radial direction from the center. The changes in the roughness over the processing time were observed until the roughness of the surface became saturated.

A second, rather subjective, method was applied to evaluate the aesthetic value of the samples after certain finishing times. It was expected that the Ra and Rz values might not be comprehensive indicators to evaluate part aesthetics. Research indicates that Rz might be linked stronger to reflexivity than Ra [22]. Perceived quality of shiny surfaces is a complex topic where physical and optical measurement alone cannot be linked completely to the quality assessment of human observers [23]. As a first attempt, we arranged a local poll with a nine people to evaluate how the perceived quality varies with processing time.

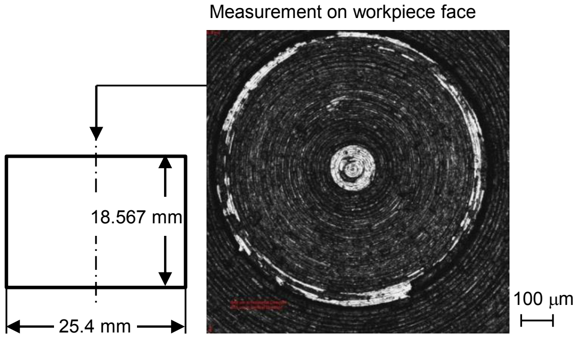

Figure 3: Image of the sample surface with the confocal laser scanning microscope

3.4. Experimental results and discussion

Three different efficiency indicators were observed over the grinding time: average roughness efficiency, $\eta_{sust@Ra}$ (equation 5), average peak-to-valley height efficiency, $\eta_{sust@Rz}$ (equation 6), and quality efficiency, $\eta_{sust@Quality}$ (equation 7). All three indicators are energy efficiencies due to the energy as denominator. Both roughness efficiencies have negative signs according to the definition in equation 4.

$$\eta_{sust@Ra} = -\frac{\Delta\, Ra}{\Delta energy} \tag{5}$$

$$\eta_{sust@Rz} = -\frac{\Delta Rz}{\Delta energy} \tag{6}$$

$$\eta_{sust@Quality} = +\frac{\Delta quality\ \ rank}{\Delta energy} \tag{7}$$

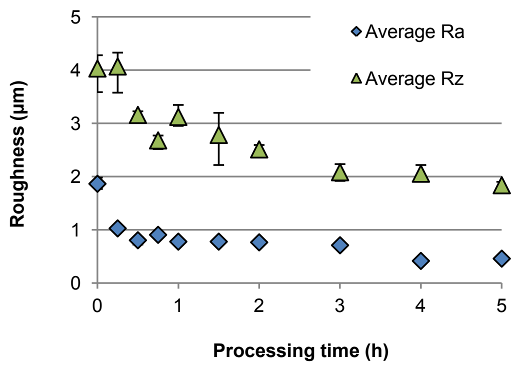

Fig.4: Average roughness (Ra) and average peak-to-valley height profile (Rz) over processing time

Figure 4 shows the variation of Ra and Rz for different processing times. It is clear that Ra and Rz decrease considerably within the first 0.5 h and then slower over time. It seems that the average Ra values fall quicker than the average Rz values. From this observation, the average Ra value might be a better indicator for the process performance and quality than the average Rz value. Another observation is that the Rz value scatters more in the beginning (first 1.5 h).

The sample aesthetic value was assessed through a poll with nine student participants. They were non-experts and were not informed of any certain application for the samples. They were asked to rank microscope pictures of the samples randomly presented on one page on a scale between 1 and 10.

The poll revealed that people ranked the quality higher when they got significantly better surface quality compared to the beginning (Fig. 5, Phase I). With further processing the rate of surface smoothing becomes slower and the surface does not vary significantly from preceding pictures (Phase II). Therefore, the participants lowered their ranking to some range close to their initial rank. At the end of the processing time the surface became remarkably smooth and shiny, and the participants ranked the product's aesthetics higher again. These results are just for this case study and cannot be generalized, but they provide a basis for discussing the proposed efficiency indicator with non-linear data. The survey procedure itself can also be improved by providing the actual test samples instead of pictures, by informing the participants more on the value or application of the samples, or providing reference pictures for comparison.

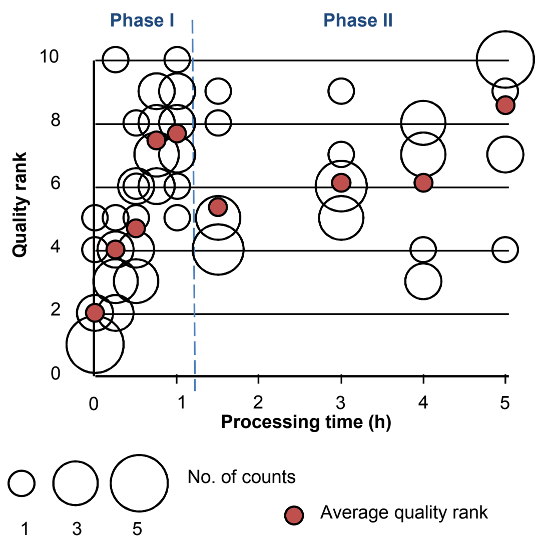

Fig 5: Subjective product quality over processing time, n = 9 participants

The three efficiency indicators have different units, but were normalized according to equation 8 to be plotted in the same curve (Fig. 6). Another way of normalization is to use a target value.

$$\text{Normalized efficiency indicator, } \overline{\eta_{sust}}(t) = \frac{\eta_{sust}(t)}{\max\left(\eta_{sust}(t_0);\eta_{sust}(t_{max})\right)} \quad (8)$$

The efficiency indicator for Ra, $\overline{\eta_{sust@Ra}}$, is highest at the beginning and gets saturated around 0% efficiency after 1.5 h (Fig. 6). A negative efficiency indicator at 0.75 h shows that the average roughness has increased instead of decreased, which can be explained by variations in the measured roughness. The data show that Ra can be decreased most efficiently in the first 15 min of the vibratory finishing process.

In contrast to Ra, the efficiency indicator for Rz, $\overline{\eta_{sust@Rz}}$ scatters a lot between -49% to 100% efficiency in the first 1 h. This aligns with the scatter of the average Rz value in Fig. 4. The normalized energy efficiency indicator $\overline{\eta_{sust@Rz}}$ is maximal at 30 min, which means Rz is decreased most efficiently at around 30 min. Again, efficiency saturates around 0 % for a longer grinding time.

The efficiency indicator for the product quality, $\overline{\eta_{sust@Quality}}$, has high values of 70% at 0.5 h and 100% at 1 h, but then drops significantly to below 0%. The negative efficiency of the quality rank at 1.5 h shows that the perceived quality dropped instead of the desired increase (Fig. 5, beginning of Phase II). The efficiency then starts rising again to a final 20 % at 5 h. This maps the trend from Fig. 5.

The zig-zag jumps in Fig. 6 are not ideal and the curves might get smoother with more data points. Nevertheless, the graph indicates that Ra-reduction is most energy efficient before a processing time of 1 h. The same applies to improving the perceived quality. The reduction of Rz is best between 30 to 45 min. This shows that the vibratory grinding process should not be extended over 1 h to be most efficient and not waste energy unnecessarily.

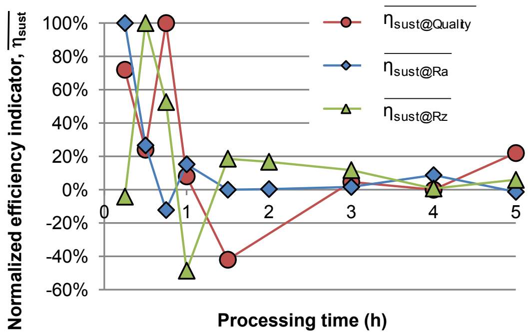

Fig 6: Normalized efficiency indicators over processing time

This discussion provides a starting point for more appropriate sustainability indicators. These sustainability indicators will be enhanced if the product application is regarded, e.g. when considering which roughness value is most important. Product performance can be significantly affected by the surface integrity.

4. Conclusion and outlook

It can be misleading if finishing operations are judged by the same sustainability and efficiency parameters used to judge manufacturing processes earlier in the process chain.

The achieved product quality needs to be taken into account for a more accurate sustainability indicator. This paper defines efficiency indicators by the ratio of produced quality or process performance to the resources applied.

A case study on vibratory grinding illustrates how these alternate indicators can be used. In particular, it discusses the energy efficiency of reducing surface roughness Ra or Rz and increasing perceived surface quality. The scatter of the efficiency indicators comes from scattering roughness and quality values. More measurements will help to find the parameter windows of highest efficiency better.

This study provides a starting point to apply more diverse performance and quality-oriented indicators for finishing processes. It exemplifies the method and challenges in using multiple criteria. In the future, more research on assessing part performance will be done, e.g. part friction behavior through measuring the friction coefficient or part wear behavior through wear tests. Extended case studies and sensitivity analyses will show the robustness of the different efficiency indicators introduced by Table 1.

Acknowledgments

The authors would like to give their sincere thanks to David Howitt and Michael Hill for allowing to use the Confocal Microscope, to the staff of the Engineering Fabrication Laboratory (EFL) to machine the sample parts and conduct the tests, and the members of the Sustainable Manufacturing Technologies (SMaT) laboratory, University of California Davis, for their extended cooperation and participation in the survey.

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